

forest habitats, commonly under canopy cover greater than 80%, in humus-rich, well-drained soils, and often on slopes or streamside microsites (Singh et al., 2026). Distribution modeling reinforces that this niche is environmentally constrained: precipitation, elevation, slope, vegetation type, and temperature range were all identified as important predictors of suitable habitat in regional models from Sikkim, Uttarakhand, and China (Tariq et al., 2021; Wang et al., 2026). Disturbed habitats repeatedly show poorer agreement with predicted suitable occurrence, implying that even climatically suitable areas may fail to support stable populations once human disturbance alters forest structure (Lepcha et al., 2019).

Habitat degradation therefore acts not only by reducing area, but by imposing ecological stress that suppresses growth and reproduction. Forest loss, fragmentation, logging, agricultural expansion, slash-and-burn cultivation, fire, landslides, grazing, trampling, and urbanization are all reported as pressures that thin populations and degrade understory conditions (Singh et al., 2026). Experimental and field evidence indicates that the species has poor adaptability to altered environments and reduced reproductive vigor under changed climatic or habitat conditions, while less than 50% shade significantly lowers seed productivity and waterlogging can be lethal. Metapopulation modeling from Sikkim further shows that disturbance and forest fragmentation substantially worsen long-term persistence, increasing extinction risk under disturbed scenarios and supporting the priority of protecting reproductive individuals in undisturbed forest matrices (Lyngdoh et al., 2018). Overall, the decline of wild *Paris* spp. reflects the interaction of commercial overexploitation with narrow habitat requirements and weak natural regeneration, making integrated in situ protection, cultivation, and habitat restoration necessary for long-term conservation (Thakur et al., 2023).

3 Current Status and Key Constraints of Artificial Germplasm Development in *Paris* spp.

3.1 Dependence on wild germplasm sources and insufficient foundations for artificial propagation

Artificial germplasm development in *Paris* spp. remains strongly dependent on wild resources, because domestication has started late and cultivated materials are still closely tied to wild-collected source populations. Several studies note that wild *P. polyphylla* has been excessively harvested and pushed toward endangerment, while cultivation has been promoted mainly as a compensatory response to the collapse of natural supplies rather than as a long-established breeding system (Puwein and Thomas, 2019; Tang et al., 2022). This weak domestication history is reflected genetically: cultivated and wild populations show little differentiation in some marker studies, with only 1.35% variation reported between 15 wild and 17 cultivated populations, indicating that cultivated stocks still largely derive from recently introduced and mixed wild origins rather than from stabilized breeding lines (Huang et al., 2019). At the same time, artificial cultivation has become essential because wild resources are now rare, and some cultivation-population studies were conducted precisely because representative planting areas already depended on scarce wild germplasm collected earlier from multiple origins (Gao et al., 2022).

The second constraint is that the biological basis for large-scale artificial propagation remains weak. *Paris* spp. show long growth cycles of about 7–10 years, extremely long dormancy release, and low reproductive efficiency, which together create a persistent bottleneck for seedling production and industrial planting (Wang et al., 2023). Seeds require more than 18 months to break dormancy in some studies, only about 40% germinate under natural conditions, and dormancy is described as morphophysiological or “double dormancy,” which makes routine nursery establishment slow and unreliable (Tang et al., 2022). Even where artificial treatment improves germination, the gains remain limited: one seed-dormancy study achieved a 40% germination rate after combined cold storage, temperature fluctuation, infrared treatment, and chemical soaking, underscoring that the propagation foundation is still technically demanding rather than straightforward. Reviews therefore conclude that conventional breeding and propagation cannot keep pace with medicinal demand, and that advanced biotechnological approaches in *Paris* remain comparatively rare or insufficiently developed (Figure 1) (Rawat et al., 2023).